FORCE OF POINT CHARGE IN A HYPERBOLIC TRAJECTORY ON A FIXED POINT CHARGE

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References: Griffiths, David J. (2007), Introduction to Electrodynamics, 3rd Edition; Pearson Education - Problem 10.24.

We'll now return to the point charge q_2 moving on a hyperbolic trajectory along the x axis. Its position is given by

$$x(t)=\sqrt{b^2+c^2t^2} \tag{1}$$

Suppose there is a second charge q_1 fixed at $x=0$. What force does q_1 exert on q_2 at time t? If we look at the problem from q_2's perspective, it needs to know what influence q_1 has on the point x that it (q_2, that is) currently occupies. In order for a signal to reach x at time t, it had to leave q_1 at time $t_r=t-\frac{x}{c}$. But since q_1 is fixed at the origin, the force that q_1 exerts on any charge q_2 at the point x is always just given by Coulomb's law without any retarded time, that is

$$F_2(t) = \frac{q_1q_2}{4\pi\varepsilon_0x^2} \tag{2}$$

$$= \frac{q_1q_2}{4\pi\varepsilon_0}\frac{1}{b^2+c^2t^2} \tag{3}$$

The total impulse delivered to q_2 is

$$I_2 = \int_{-\infty}^{\infty}F_2(t)\,dt \tag{4}$$

$$= \frac{q_1q_2}{4\pi\varepsilon_0b^2}\int_{-\infty}^{\infty}\frac{1}{1+\frac{c^2}{b^2}t^2}dt \tag{5}$$

$$= \frac{q_1q_2}{4\pi\varepsilon_0bc} \tag{6}$$

To calculate the force q_2 exerts on q_1 we *do* need the retarded time, since q_2 is moving. [Incidentally, it might seem that by considering q_1 as at rest and q_2 as moving, and treating the two cases differently, we're violating the principle of relativity, but we're not. The reason is that q_2 is not in an inertial frame; the hyperbolic trajectory means that its velocity is never constant, so q_1 and q_2 are not equivalent.]

The retarded time is calculated from

$$|\mathbf{r}-\mathbf{w}(t_r)| = c(t-t_r) \tag{7}$$

Here $\mathbf{r}=0$ is the location of q_1 and $\mathbf{w}(t_r) = \sqrt{b^2+c^2t_r^2}\,\hat{\mathbf{x}}$ is the position of q_2. We get

$$\sqrt{b^2+c^2t_r^2} = c(t-t_r) \tag{8}$$

$$t_r = \frac{t}{2}-\frac{b^2}{2c^2t} \tag{9}$$

Note that as $t\to 0$, $t_r\to-\infty$ so q_2 is not visible to q_1 before $t=0$, so the retarded potential is zero for $t<0$. The force for $t>0$ is therefore (the minus sign indicates the force is to the left if both charges are the same sign)

$$F_1(t) = -\frac{q_1q_2}{4\pi\varepsilon_0}\frac{1}{b^2+\frac{c^2}{4}\left(t-\frac{b^2}{c^2t}\right)^2} \tag{10}$$

$$= -\frac{q_1q_2}{\pi\varepsilon_0}\frac{c^2t^2}{4c^2b^2t^2+\left(c^2t^2-b^2\right)^2} \tag{11}$$

$$= -\frac{q_1q_2}{\pi\varepsilon_0}\frac{c^2t^2}{\left(c^2t^2+b^2\right)^2} \tag{12}$$

The total impulse is found by integrating F_1 from $t=0$ to infinity, since there is no force for $t<0$.

$$I_1 = -\frac{q_1q_2}{\pi\varepsilon_0}\int_0^\infty\frac{c^2t^2}{\left(c^2t^2+b^2\right)^2}dt \tag{13}$$

$$= -\frac{q_1q_2}{4\pi\varepsilon_0 bc} \tag{14}$$

[The integral can be done by parts, although I used Maple.] Thus the two impulses are equal and opposite.